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# Moving towards a resilient multi-modal transport network: Great Britain's case study

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## Abstract

The continued operation of transportation network is vital to the economy of a nation. However, natural hazards, human-induced threats and accidents continue to cause disruptions to these networks. A significant amount of work has been done to examine road and rail transport networks on a national scale. Yet recent data for Great Britain shows that there were delays on the Strategic Road Network and a significant percentage of trains did not run on time. Also, whilst many cities are moving towards integrated local transport such a move at a national level is relatively unknown. The aim of this paper is to examine the resilience benefits to be gained from such a unified multi-modal network at a national level.

A case study approach is followed where the characteristics and vulnerabilities of individual networks are assessed and compared with that of the multi-modal transport network. The key networks of highways, railways and airport within Great Britain have been modelled, ultimately leading to an interconnected multi-modal transport network. A range of analyses have been conducted using the suite of graph and network algorithms. These show that while there is a reduction in the vulnerability of several nodes when considering multi-modal transport network, some of the nodes continue to play a dominant role and measures should be taken to shift the reliance from them. A distinct critical node was noted in each region, while the lack of resilience of the connections between England and Wales is another leading issue. The need to undergo further works that will maximise the investment being made in HS2 was also identified. A case for policy shifts away from using population as a critical factor in future transport planning, as well as introducing a specific multi-modal policy to sit alongside each individual network policy is made.

## Keywords

Multi-modal transport, network science, vulnerability analysis, resilience.

## Introduction

Great Britain's major transportation network of Highways, Railways, and Airports enable the movement of vast numbers of people and commercial goods, making it an essential part of the economy<sup>1</sup>. Despite this,

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<sup>1</sup> House of Commons Transport Committee. The Transport Committee, (The Stationery Office, 2011).

every day, people and commercial goods spend numerous hours stuck in traffic jams and hold ups, which then have knock on effects to the rest of the network. According to the Department for Transport, in the financial year 2015-2016 10.9% of trains and 23% of flights did not run on time, while there was an average delay of 8.9 seconds per vehicle mile on the Strategic Road Network in England<sup>2</sup>. There is a vast spectrum of events, ranging from human-induced threats such as climate change or terrorist attacks, to natural hazards such as floods or storms. It is essential to minimise any drop in the functionality of the transport network due to shocks and stresses and to enable quick recovery when it does happen – two essential aspects which govern resilience. There is a large body of research work<sup>3 4 5 6</sup> that looks at the vulnerability of each transport network individually. Transport bodies also publish details of their planned work<sup>7 8 9</sup> but there does not appear to be a unified approach to national multi-modal transport network. The aim of this study is to improve the resilience of Great Britain's multi-modal transport network by examining the vulnerability of each individual network as well as the combined network.

The paper is organised as follows. Firstly, we give details of the modelling of Great Britain's multi-modal transport network. Secondly, we compare the form of individual and combined transport networks using a range of indicators drawing upon network science literature. Thirdly, we present results for the vulnerability analysis of the multi-modal transport network and compare/contrast with those of the individual networks.

## Modelling of multi-modal network

For this study, network science approach is used to represent and analyse the major national transport network for three modes of travel, individually as well as a unified multi-modal network. A network is defined by a characteristic set of system components, known as nodes and links<sup>10</sup>. Nodes have been selected based on locations determined to be economic hubs, key transport links, geographically significant areas i.e. they help to provide an image of the entire country, or a combination of these factors. This enables observations to be made on a national level without the need for specific local details. To simplify the analysis, each node covers all types of transport links within its general area. Further, only one link of each type can exist between any two nodes. The path length of each link is equal to the fastest possible journey time between the connecting nodes for each mode of travel.

The road network model represents the motorways and major trunk roads across Great Britain, with network data from Highways England<sup>11</sup>, Welsh assembly<sup>12</sup> and The Scottish Government<sup>13</sup>, and path length data from Google<sup>14</sup>. The rail network consists of the lines managed by National Rail, with path length data directly from National Rail<sup>15</sup>. The airport network represents the flight paths between major airports in

<sup>2</sup> Department for Transport. Single departmental plan 2015 to 2020, (Department for Transport, 2016).

<sup>3</sup> Mattsson, L. & Jenelius, E. Vulnerability and resilience of transport systems - a discussion of recent research. *Transportation Research Part A*, 81, (2015).

<sup>4</sup> Zio, E., Sansavini, G., Maja, R. & Marchionni, G. An analytical approach to the safety of road networks. *International Journal of Reliability, Quality and Safety Engineering*, 15(1), (2011).

<sup>5</sup> Dunn, S. & Wilkinson, S.M. Identifying Critical Components in Infrastructure Networks Using Network Topology. (2013).

<sup>6</sup> Cai, K.-Q., Zhang, J., Du, W. & Cao, X. Analysis of the Chinese air route network as a complex network. *Chinese Physics B*, 21(2), (2012).

<sup>7</sup> Highways England. Highways England Delivery Plan 2016 to 2017, (Highways England, 2016).

<sup>8</sup> Network Rail. Annual report and accounts 2016, Network Rail Limited, (2016).

<sup>9</sup> Civil Aviation Authority. Annual Reports and Accounts 2015/16, (Civil Aviation Authority, 2016)

<sup>10</sup> Barabási, A.-L. *Network Science*. 1st Edition ed. (Cambridge University Press, 2016)

<sup>11</sup> Highways England. Roads managed by Highways England. (2014).

<sup>12</sup> Welsh Government. Traffic Wales. (2013). [Online]

<sup>13</sup> Transport Scotland. Trunk Road Network Height Map. (2007) [Online]

<sup>14</sup> Google. Google Maps. (2017).

<sup>15</sup> National Rail. National Rail Enquiries, (2017).

Great Britain i.e. those airports with over 400,000 total passengers per year according to the CAA<sup>16</sup>, with path length data from Skyscanner<sup>17</sup>. Smaller scale forms of transport, including cycling and walking, are not included due to their limited impact on a network of national scale. The modelled networks are shown in Figure 1 and their characteristics are listed in Table 1. Degree is the number of links a node has to other nodes. A path length is the shortest possible journey time between any pair of nodes. The network diameter is the maximal path length within the network i.e. the longest journey between nodes.

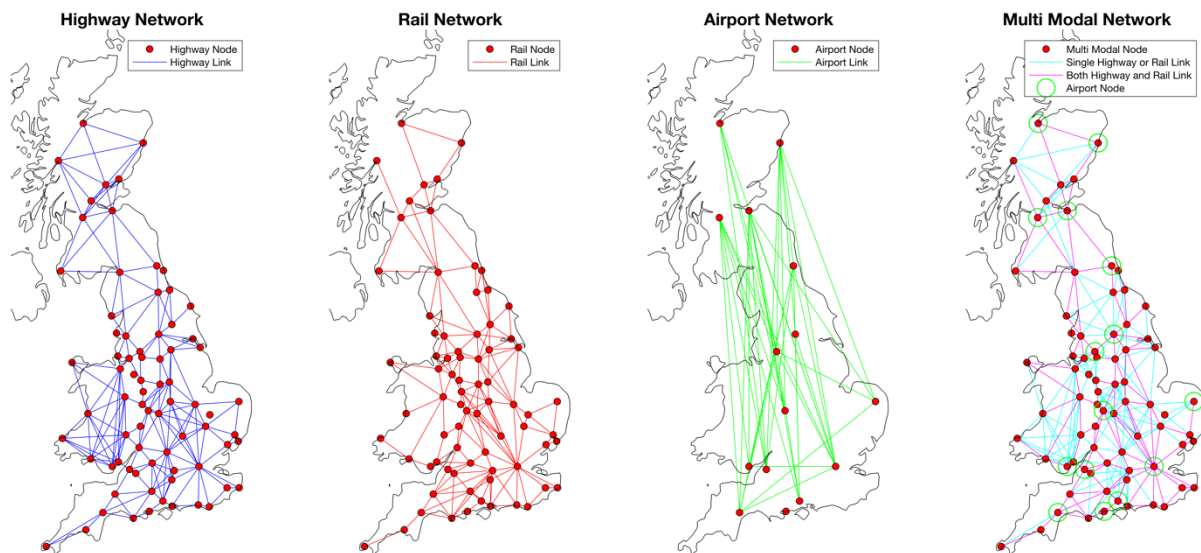


Figure 1: Modelling of independent networks and the multi-modal network

Table 1: Graph-theoretic properties of each network

	Highway Network	Rail Network	Airport Network	Multi-Modal Network
No. of Nodes in Network	74	76	15	76
Total Network Degrees	392	362	80	834
Total Network Links	196	181	40	417
Average Nodal Degree	5.1579	4.7632	1.0526	10.974
Network Diameter (mins)	916	767	150	485
Average Path Length (mins)	285.6	210.6	106.2	183.7

The airport network covers a much smaller number of nodes and so is difficult to compare, however the highway and rail networks have almost the same selection of available nodes. The rail network has a lower network diameter and lower average path length, indicating lower overall travel times. The multi-modal network has links equal to the sum of the three-independent networks, with an average path length and network diameter well below that of the highway and rail networks. However, this assumes no time is lost in changing modes between the highway and rail network, and sets a standard time of one hour for changing to the airport network. These conditions have been set as there is far too much uncertainty to accurately predict changeover times, however they should have minimal impact on the outcome of the study, as it is concerned with the vulnerability of the network rather than predicting travel times.

<sup>16</sup> Civil Aviation Authority. Terminal and Transit Passengers 2015, (Civil Aviation Authority, 2016).

<sup>17</sup> Skyscanner Ltd. Skyscanner. (2016).

## Analysis of individual and multi-modal networks

A range of analyses have been conducted on these networks to study the impact of hazard-independent scenarios (see Figure 2 for a schema). The primary tool utilised was MATLAB, alongside the Brain Connectivity Toolbox<sup>18</sup>. The computationally inexpensive nature of these approaches meant that large networks can be appropriately modelled and analysed. The results take the form of changes in network performance metrics<sup>19</sup> outlined below. These were chosen due to their simplicity in revealing clear trends, even on a model of this scale.

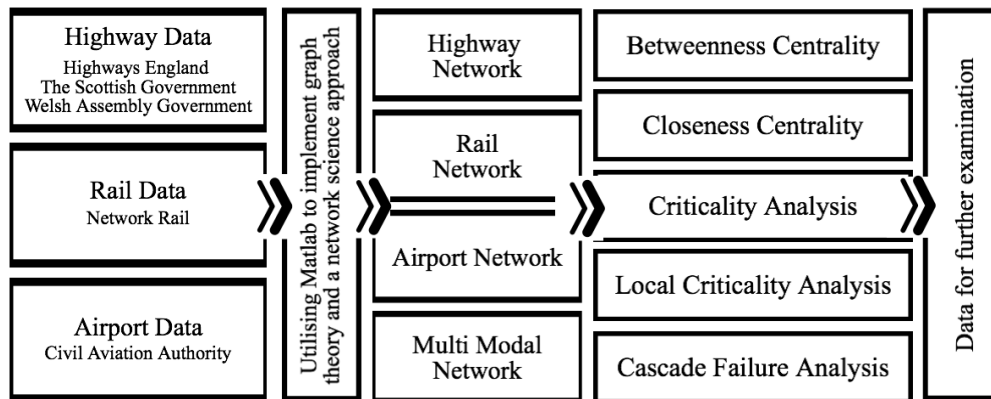


Figure 2: A schematic of the methodology showing the inputs and outputs

**Betweenness Centrality:** This measures the consistency with which a node or a link appears along the shortest path between two nodes, for all possible journeys, giving an indication of how often it is used. This can be used to examine the global importance of each node or link, as well as the extra demand created by the removal of other nodes or links.

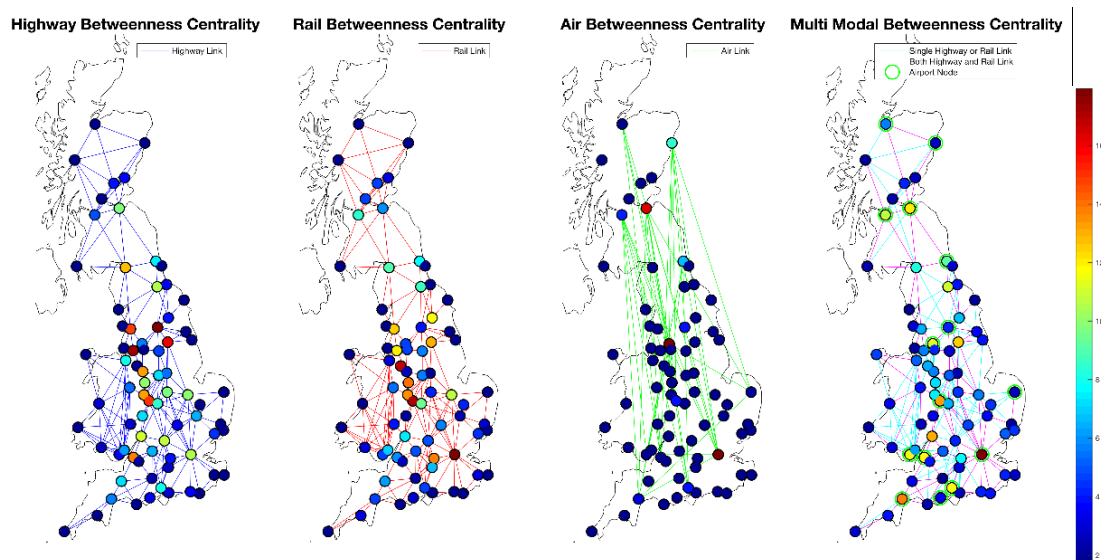


Figure 3: Node Betweenness Centrality for each network (highway, rail, airport and multi-modal) - normalised with respect to maximum of each network

<sup>18</sup> Rubinova, M. & Sporns, O. Complex network measures of brain connectivity: Uses and interpretations. (Elsevier, 2010).

<sup>19</sup> Lewis, T. G. Network Science, (John Wiley, 2009).

**Closeness Centrality:** This calculates the inverse sum of the shortest path lengths between a node and all other nodes. The higher the closeness centrality the closer the node to all other nodes, giving an indication of accessibility. This is an important local attribute of each node, and can be used to measure the reduction in accessibility due to the loss of key nodes.

**Network Efficiency:** Network efficiency is defined as the average inverse shortest path length for all possible journeys within the network, i.e. a shorter average path length means greater efficiency. This can be used to study the impact of an event.

**Criticality:** In this study, criticality has been assessed either globally by measuring the drop-in network efficiency following the loss of a node (labelled as Criticality Analysis in Figure 2), or locally by observing the increase in average path length for the nodes neighbouring damaged node (labelled as Local Criticality Analysis).

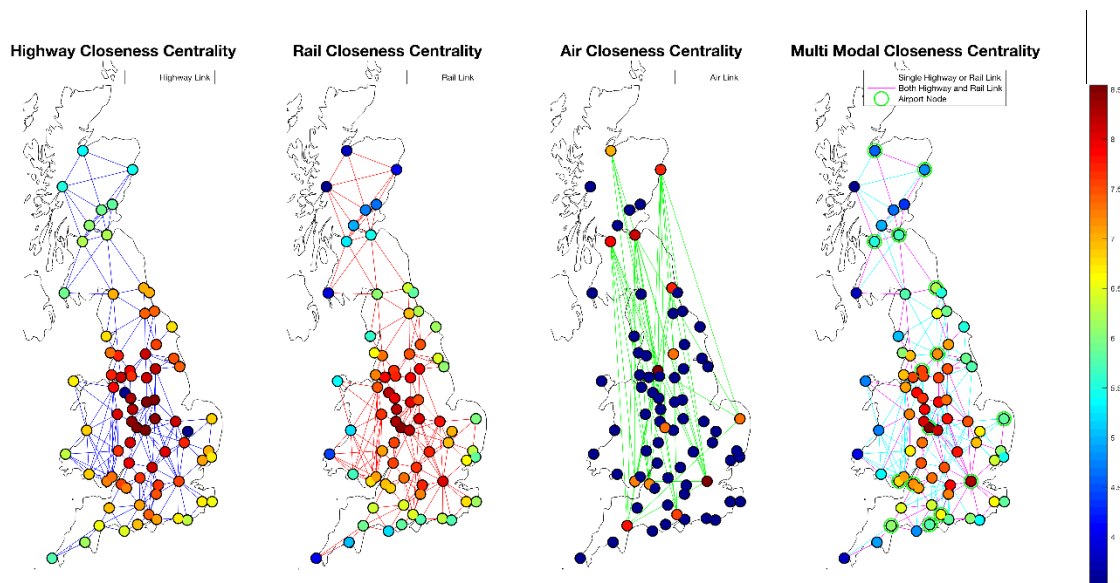


Figure 4: Closeness Centrality for each network (highway, rail, airport and multi-modal)

From a betweenness centrality perspective (see Figure 3), nodes such as London, Birmingham, and Exeter are the nodes present on the most routes across each network, as they control movement between large geographic regions i.e. north to south or east to west. However, for the multi-modal network the distribution of betweenness centrality is more uniform. For closeness centrality (see Figure 4), London and the entire midlands area surrounding Birmingham are the most accessible nodes for each network. Birmingham controls much of the movement from the north to the south also.

## Vulnerability analysis of multi-modal network

An essential vulnerability analysis technique is applying **N-k scenarios** to a system (i.e. removing k number of nodes (links) from the system with N nodes (links)) and studying the impact this has. Here results for only N-1 scenarios are presented though many natural hazards have the potential to damage several nodes. Figure 5 shows the ranking of nodes global and local criticality, alongside the global criticality of the links. It is observed that the nodes located along the coast generally have a low global criticality, due to their limited connections, as they are more end destinations than key transit points. The central spine of Great Britain, centred around Birmingham has a high proportion of high criticality nodes - its geographic

location means it controls access to a huge portion of the network. Despite this, the high density of nodes in this area provides redundancy, meaning no one node is vastly more critical than the rest.

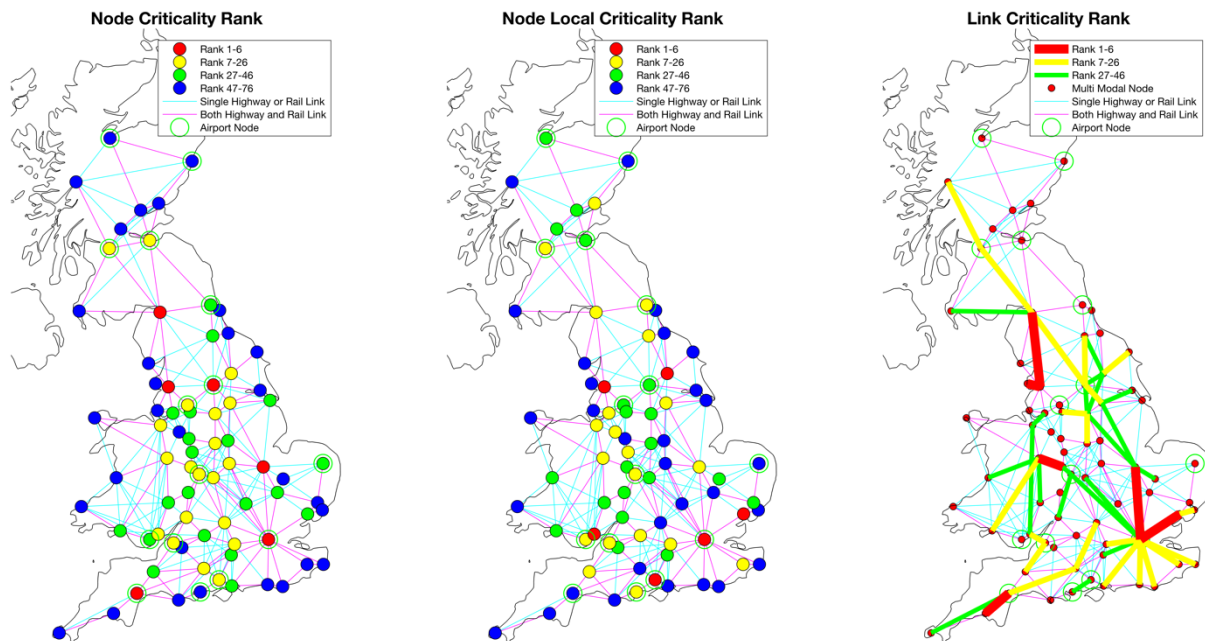


Figure 5: Results of N-1 scenarios: (a) Node criticality – global, (b) Node criticality – local, (c) Link criticality (global)

The highest globally critical nodes are located around this central spine, and are well spread across the entire network. Each of these nodes generally is in one of the statistical regions of Great Britain, and is the key node within that region which allows movement from it to other regions, with no other alternative node that can be used within the region, which is what makes them so critical. Figure 5 shows that local criticality follows a similar principle, although with slightly different key nodes. These highly critical nodes are therefore a key area of focus in reducing the vulnerability of the whole network, through alternate routes to provide redundancy, or alternatively the realigning of recovery services to these areas to ensure that any incidents can be cleared as quickly as possible. It must be noted that this analysis focuses only on the form of the network, and so an additional cost benefit analysis that considers the demand on these areas should also be looked at.

Inspection of the link criticality results in Figure 5(c) shows a very similar trend, with the most critical links located around the central spine of Great Britain. Several of the most critical links connect nodes which are also the most critical global nodes, showing a close relationship between the most critical nodes and links. A further observation from this study is the existence of a critical node for each region of Great Britain (Table 2), which controls most of the movement throughout that region, with very few alternative nodes in the event of the most critical node failing.

Table 2: Critical node for each region of Great Britain

Region	Scotland	North West	Yorkshire and North East	West Midlands	Wales	East and East Midlands	South West	South East
Node	Carlisle	Preston	Doncaster	Birmingham	Newport	Peterborough	Exeter	London



A **cascade failure** is the progressive failure of the network. When one node fails, demand shifts to nodes around it, which causes these nodes to fail until a stable point is reached. Data from this analysis can be applied to a complete node failure, or a partial closure of a node due to heavy disruption and congestion. This type of analysis represents the full potential impact a node failure can have.

For this type of analysis, betweenness centrality was used as the measure of demand on each node. This refers to a flow model which assumes infinite capacities of nodes and links, but that is not the case in practice, hence a limit of a 50% increase in betweenness centrality was defined for the failure of a node or link to explore the failure cascade. This is an arbitrary limit, so results are presented relative to each other, rather than as absolute values. Each node is removed in turn, and the betweenness centrality of each node recalculated, with nodes above the failure limit also removed. This process is repeated until a stable point is reached (i.e. no remaining nodes with more than a 50% increase in their original betweenness centrality). Here, each node's cascade failure was assessed from the reduction in global network efficiency and the results are shown in Figure 6.

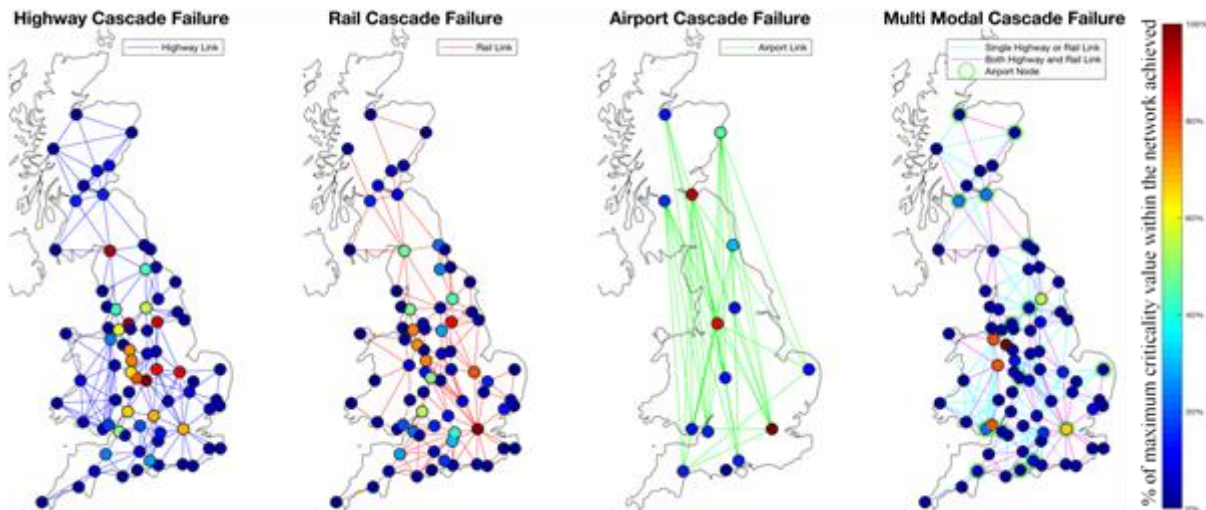


Figure 6: Visualisation of the Cascade Failure Criticality for node loss in each network

From Figure 6, firstly considering both the Highway and Rail network, London is at least moderately critical, and the high demand through London ensures many of the nodes surrounding it have a low criticality, which is a further reason for ensuring the continued security of London. Most critical nodes are concentrated across the centre of the country, and extend through the north west up to Carlisle. Specific nodes around the edge of the central spine of Great Britain, which control much of the movement through the geographic region in which they are located are still highly critical due to the number of journeys they facilitate. Additionally, nodes within this central spine which were previously not individually very critical are now extremely critical. Although the high number of nodes in this area provide redundancy, the large number of routes through this area means they are not enough to prevent a cascade failure. This is therefore a key region to focus on in terms of equally distributing demand between each node when a failure does take place i.e. encouraging the use of several paths not just the shortest path. It can also be noted that a specific corridor of criticality exists from the midlands area around Birmingham, up through the North West via Warrington, and onwards to Carlisle. This route should therefore be another primary area of focus for Highways England and National Rail, although this would require cost benefit analysis as this analysis looks only at the form of the network. Finally, for the air network, London, Edinburgh, and



Manchester rank as the most critical node by a considerable margin, which is due to their geographic positions as the primary nodes in the north, middle, and south of Great Britain. Investment in other airports within proximity to these nodes is therefore the principal method of reducing this criticality.

For the multi-modal network, the high number of connections provide enough redundancy to prevent a major cascade failure for the bulk of the network. While London retains a high criticality, the major area of focus is the high criticality of the nodes that connect England to Wales, as there are only four connecting nodes between the two nations. Future work by the government to increase this number of connecting nodes is a vital step to ensure the security of movement between both regions.

**Spearman's rank correlation:** Despite the focus of this study being on the multi-modal aspect of the transport network, the key to improving the multi-modal network is to improve each individual network such that they most effectively contribute to the multi-modal network. Hence, the correlation between their rankings is examined in Table 3. One initial trend is the overall lack of correlation with the Airport network, which could be attributed to its smaller size, limiting its use for long distance journeys. This conversely identifies the highway and rail as the networks for future investment.

Table 3: Spearman's Rank Correlation between rankings of different networks for N-1 scenarios

GLOBAL NODE CRITICALITY	Highway	Rail	Airport	Multi-modal
Highway		0.667	0.115	0.889
Rail	0.667		0.042	0.798
Airport	0.115	0.042		0.353
Multi-modal	0.889	0.798	0.353	

## Discussion

**Local vs. global importance:** There are many stakeholders who are each interested in a different set of outputs. The two main stakeholders to consider are global stakeholders i.e. the British government, who are concerned with the overall performance of the transport network, and local stakeholders i.e. local authorities, who are concerned with the performance of the network in their area. The outputs defined as pertaining to global stakeholders are betweenness centrality, criticality and cascade failure criticality. For local stakeholders, the relevant outputs are closeness centrality and local node criticality.

Figure 7 shows the balance between global and local importance of nodes for the multi-modal network. London and Birmingham are found to be important to both categories of stakeholders. Exeter, Glasgow, Edinburgh, and Carlisle are nodes which sway greatly towards global importance as they have lots of links through them. These nodes are thus the key areas where the government should look to implement major schemes as the local authorities are unlikely to implement such schemes due to the limited benefit for the local area. The nodes that sway most towards local importance are coastal nodes such as Southampton and Liverpool, with large populations. These also have large amounts of links however they are final destinations rather than stops along longer routes, resulting in lower levels of importance globally. These are areas where the government should allow local authorities to focus their efforts, rather than implementing large schemes themselves.

**High Speed 2 (HS2):** A large part of the government's plan to enable new economic development across the country in terms of improving the rail network is HS2. This would see the construction of a high-speed

rail line from London to Manchester and Leeds, via Birmingham. The scheme would look to deliver a total investment of £55.7 billion (at 2015 prices), with completion by 2033<sup>20</sup>.

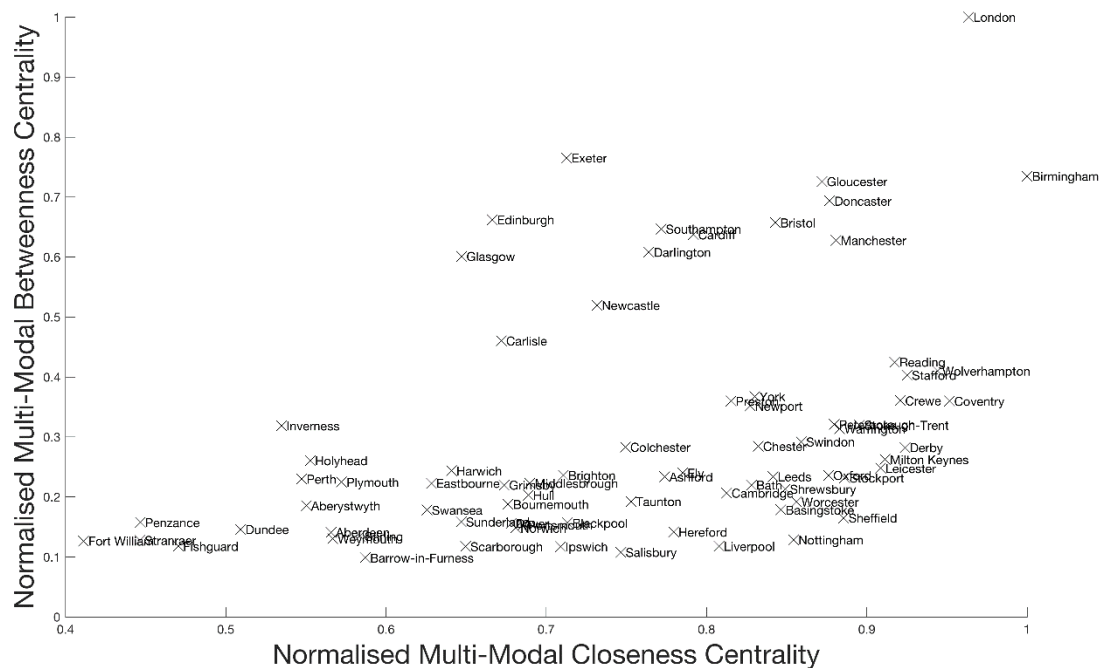


Figure 7: Global importance (betweenness centrality) vs. local importance (closeness centrality) for multi-modal network

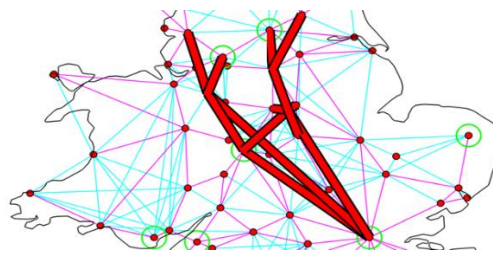


Figure 8: Modelling of the rail links that will be created by the implementation of High Speed 2

To incorporate HS2 into the existing model the new links and their journey times were added into the rail and multi-modal networks (Figure 8), which also involved the creation of a new node, The East Midlands Hub, which will be situated between Derby and Nottingham. The model was then re-simulated using these new inputs and the network characteristics are compared in Table 3. The addition of HS2 results in a significant improvement in average journey times across the rail (11% decrease) and multi-modal (9% decrease) networks.

Table 3: Characteristic Network Properties before and after the implementation of High Speed 2

	Rail Network Characteristics			Multi-Modal Network Characteristics		
	Normal	HS2	Difference	Normal	HS2	Difference
Total Degrees	362	382	+20	834	854	+20
Total Links	181	191	+10	417	427	+10
Average Degree	4.763	4.961	0.198	10.974	11.091	0.117
Network Diameter	767	724	-43	485	485	0
Average Path Length	210.57	187.41	-23	183.68	167.86	-16

<sup>20</sup> Department for Transport. High Speed Two: East and West The next steps to Crewe and beyond, (Department for Transport, 2015).

On multi-modal network, the betweenness centrality of Crewe and Sheffield increase significantly, making them much more significant parts of the network. The new East Midlands Hub also comes in as the 18th highest ranked node on the multi-modal network, which is significant considering that it is only a part of the rail network. While the rank of Birmingham and other surrounding nodes in the midlands that can now be bypassed due to HS2 fall significantly. The London to Crewe link also becomes the most central link within the network. On the rail network, there is a similar trend, however the overall effect is much more pronounced. The only significant change in node criticality is that of Crewe which sees a huge rise in its ranking for the multi-modal and rail networks. To ensure that HS2 is most effective, it is therefore clear a large amount of focus needs to be placed on Crewe and Sheffield, and associated nodes along the routes from London, through them, and onto the north west and north east respectively. In Crewe's case, linking it to the major highway network is a significant part of this.

**Population vs. network vulnerability:** Population seems to be a major factor in deciding where new schemes are located; for example, HS2 links together 8 of the 10 largest cities in the country. However, a graph of the population rank of each node against its overall rank based on graph-theoretic metrics (Figure 9) does not suggest a strong correlation (Spearman's rank correlation=0.538). Thus, future transport policy must do more to specifically focus on network vulnerability.

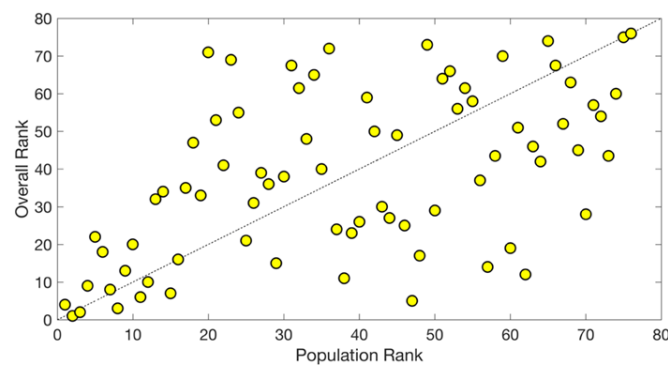


Figure 9: Relationship between overall rank (based on examined graph-theoretic metrics) and population rank for each node

## Conclusion

This study has examined the Great Britain's multi-modal transport network on a national scale, moving away from solely focusing on individual networks. Analyses were conducted to obtain graph-theoretic metrics including betweenness centrality, closeness centrality, global and local criticalities, and cascading failures. These reveal several defining network characteristics which could be used to advantage to improve the resilience of the transportation network. A shift in reliance away from Birmingham and the West Midlands, alongside the implementation of a cascade failure action plan for the West Midlands region is needed. The presence of a distinct critical node for each region was noted, necessitating the creation of regional action plans to minimise the consequences of a failure of one of these nodes. Additionally, there is a need to increase the number of multi-modal links between England and Wales. Transportation projects should consider population as well as network vulnerability. Work needs to take place between Highways England and Network Rail to ensure major schemes like HS2 are most effectively implemented for all users of the multi-modal network. These results should be further analysed in the light of the assumptions made and the likely demands on the networks. Future work should also examine more complex failure scenarios where multiple nodes or links are affected.